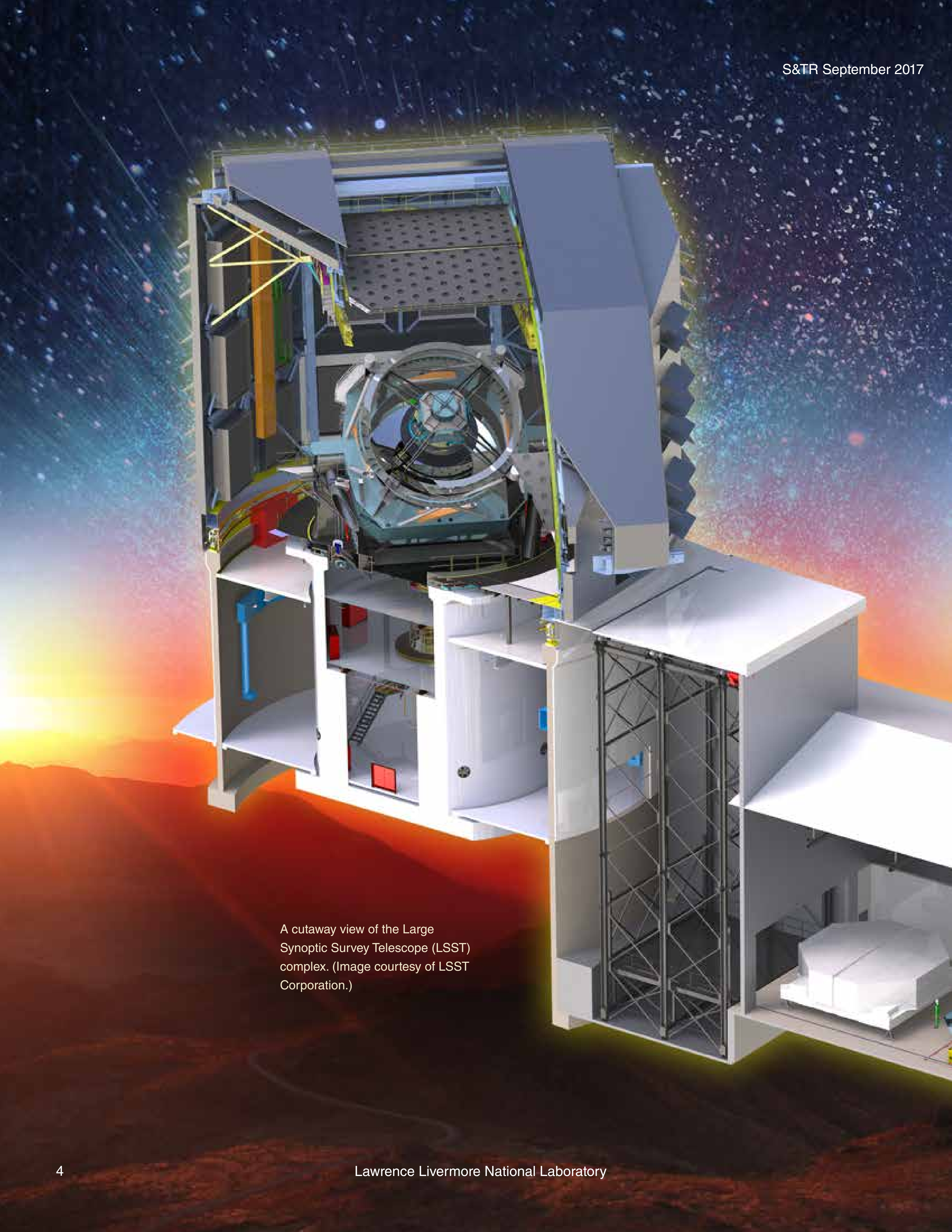


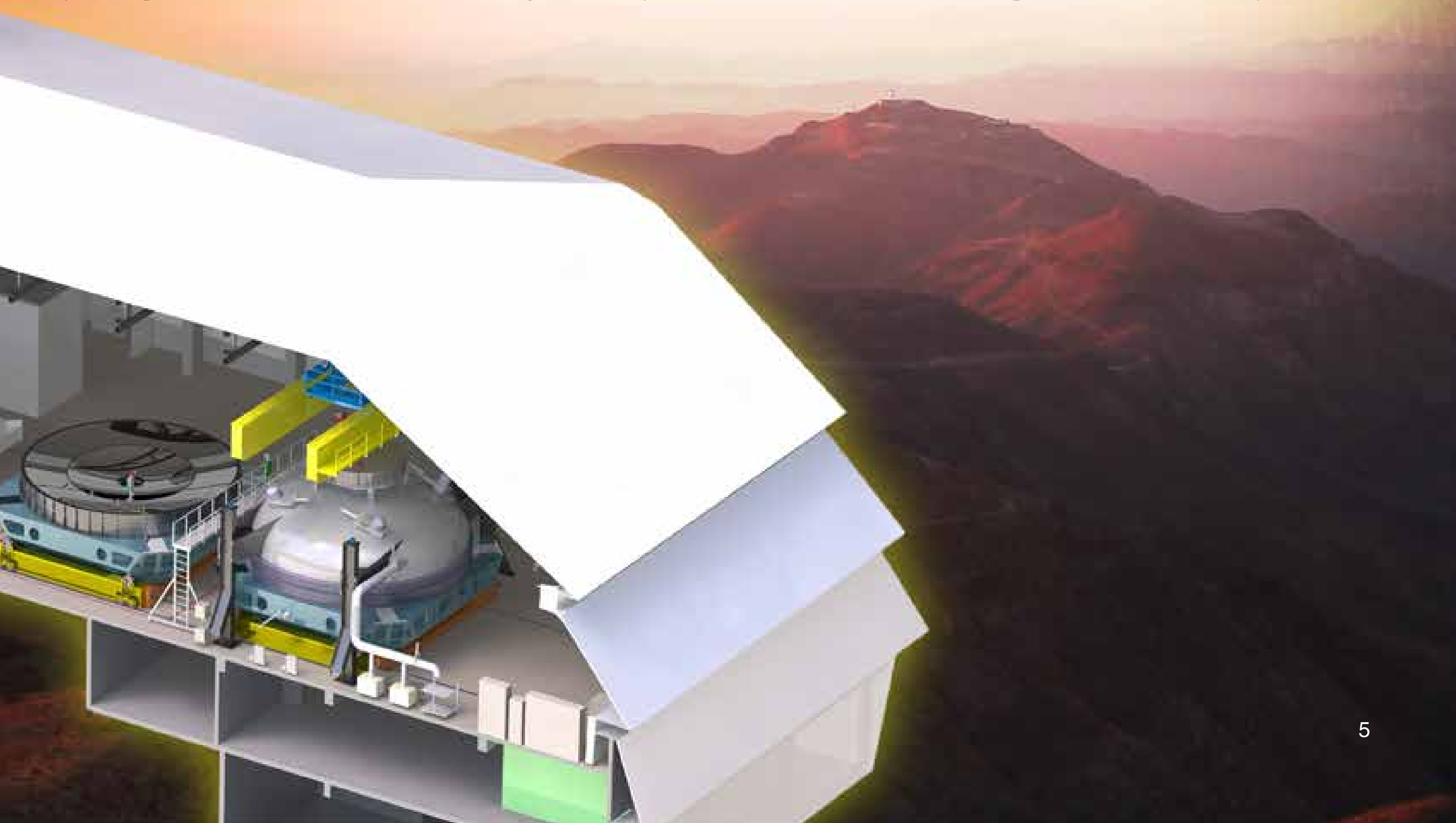
A cutaway view of the Large Synoptic Survey Telescope (LSST) complex. (Image courtesy of LSST Corporation.)

THE WIDEST, DEEPEST IMAGES OF A DYNAMIC UNIVERSE

The starry sky may not give the impression of much happening in the cosmos, but beyond our vision occur the wildest of events. A new telescope is set to reveal these intriguing phenomena to an unprecedented degree.

UNAIDED and under the darkest conditions, the human eye can see only about 9,000 stars around Earth. The Large Synoptic Survey Telescope (LSST)—looking at only half of the night sky—is expected to detect an estimated 17 billion stars and discover so much more over the course of a 10-year mission. However, without the crucial roles played by Lawrence Livermore, this major new telescope, now being constructed in Chile, might have only been science fiction instead of being on the verge of delivering game-changing science.

From icy comets to stealthy planetoids, exploding stars, newborn galaxies, and everything in between, billions of objects are expected to be discovered by LSST



during its survey of the universe. What also thrills stargazers and researchers alike is its great potential to yield a myriad of unexpected discoveries. LSST's core science areas are investigating the nature of dark matter and dark energy; cataloging moving bodies in the solar system, including hazardous asteroids; exploring the changing sky; and further understanding the formation and structure of the Milky Way.

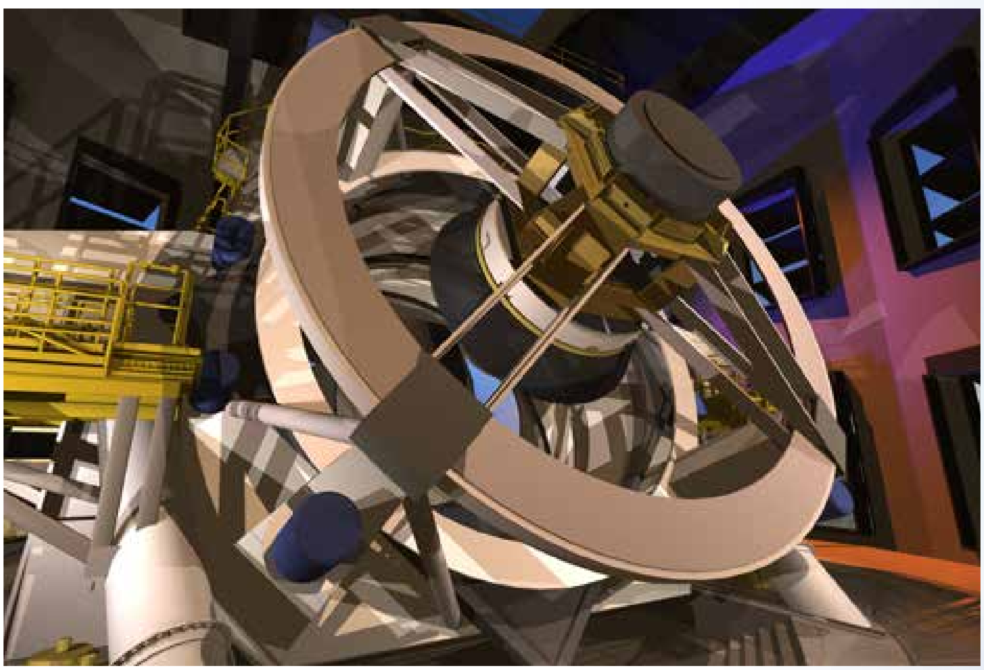
Ground- and space-based telescopes are typically optimized to address one or two of these areas, resulting in designs that inhibit study in the others. However, the ingenuity of LSST's design, its grand size, and its use of groundbreaking technology promise to open the universe to exploration leaps ahead of what the telescopes of today can do. LSST director Steve Kahn, a physicist at Stanford University and the SLAC National Accelerator Laboratory, says, "Livermore has played a very significant technical role in the camera and a historically important role in the telescope design." Livermore's researchers made essential contributions to LSST's optical design, lens and mirror fabrication, the way LSST will survey the sky, how it compensates for atmospheric turbulence and gravity, and more. Kahn adds, "Livermore also plays a substantial role in the science of dark energy."

Livermore joins forces with a team of hundreds representing dozens of domestic institutions and international contributors from more than twenty countries. The consortium also relies on industry experts to fabricate components that have designs pushing well beyond current boundaries. LSST Corporation formed in 2002 and began privately funding the early development of LSST, including mirror fabrication and survey operations. The Department of Energy (DOE) funds camera fabrication, while the National Science Foundation funds the remaining telescope fabrication, facility construction, data management, and education and outreach efforts.

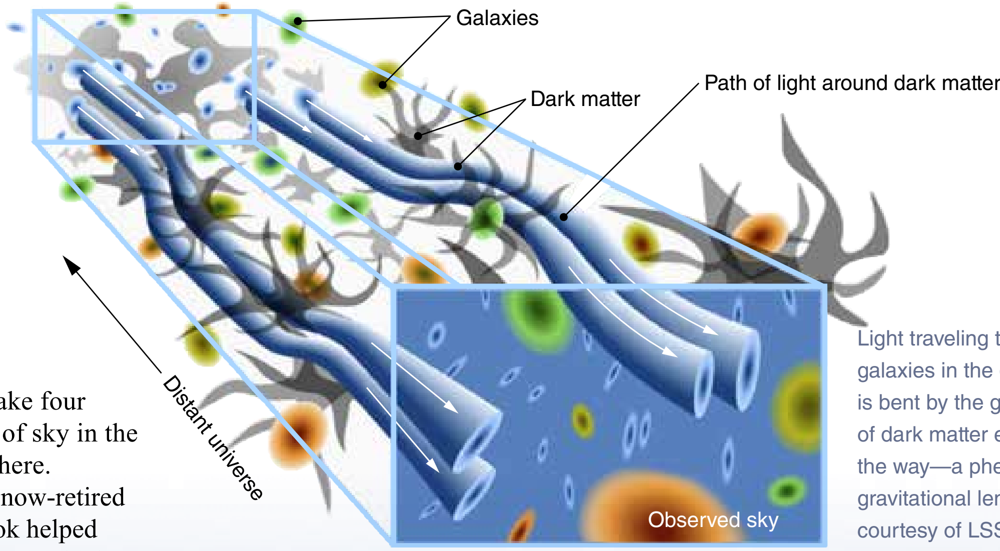
The telescope is scheduled to begin full scientific operations in 2023. The first stone of the LSST Summit Facility was laid in April 2015 on El Peñón, a peak 2,682 meters high along the Cerro Pachón ridge in the Andes Mountains and located 354 kilometers north of Santiago, the capital of Chile. Locations around the world were scrutinized to find the most suitable site. Chile—already a world leader as a site for modern mountaintop telescopes—won out by offering the best combination of high altitude, for less atmosphere to peer through; desolation, for less light pollution; dry environment, for fewer cloudy days; stable air, for less turbulence; and the infrastructure necessary for construction and operation.

The First Universal Motion Picture

Every night for 10 years, LSST will conduct a wide, deep, and fast survey comprising roughly 1,000 "visits" that together will canvas a third of the sky above the Southern Hemisphere. In each visit, the telescope will capture a pair of 15-second exposures before moving on to a new location. Taking back-to-back exposures of a single patch of sky will help eliminate erroneous detections, such as when cosmic rays strike the camera's detector. After finishing a visit, a neighboring part of the sky typically will be chosen to minimize slew time—the approximate 5 seconds that LSST will need to reposition itself and for vibrations to settle down to a level that will not impede image resolution. However, LSST can respond to sudden changes in surrounding conditions, such as clouds appearing, by optimizing its



Despite its compact design, LSST weighs a massive 350 tons. Of this total, 300 tons comprise moveable parts. (Image courtesy of LSST Corporation.)



Light traveling to Earth from galaxies in the distant universe is bent by the gravitational force of dark matter encountered along the way—a phenomenon called gravitational lensing. (Image courtesy of LSST Corporation.)

survey pattern on the fly and rapidly switching to a filter that provides more favorable viewing. Furthermore, for every spot visited, LSST will return an hour later to take another pair of exposures. Thus every three days LSST will take four images of every single patch of sky in the observable Southern Hemisphere.

In the early days of LSST, now-retired Livermore physicist Kem Cook helped develop the operations simulator, which schedules where the telescope will point for every exposure over the 10 years. Kahn says, "Cook's scientific interests were in time domain astronomy—looking at how things changed with time. How we sample the sky is key to the time history of all these exposures." Over 10 years, the telescope will generate 5.5 million individual images. When stitched together like individual movie frames, the images will yield what LSST's builders call "the first motion picture of the universe." In fact, the total image data produced will be the equivalent of 15,500 feature-length motion pictures on 35-millimeter film. This moving picture prowess will evolve astronomy from traditional static views of the universe to stellar time-lapse photography, like studying how a bird flies in real time instead of only looking at individual photographs.

Illuminating the Dark

In a galaxy far, far away is the preamble to a well-known science-fiction epic, but 20 billion very far-away galaxies is what LSST expects to view. Instead of the "dark side," the telescope will investigate the mysteries of dark matter and dark energy. A cosmic accounting of all the solids, liquids, gases, and other identifiable forms of matter does not even come close to estimates of the grand total of all matter in the universe. "Dark matter is about 95 percent of the total mass that we can infer exists in the universe," explains Michael Schneider, the physicist leading Livermore's LSST science efforts, which are funded primarily by the Laboratory Directed Research and Development (LDRD) Program and DOE's

Construction of LSST is well under way on the 2,682-meter El Peñón peak in the Andes Mountains of Chile, as shown in this photograph taken in May 2017. (Photograph courtesy of LSST Corporation.)

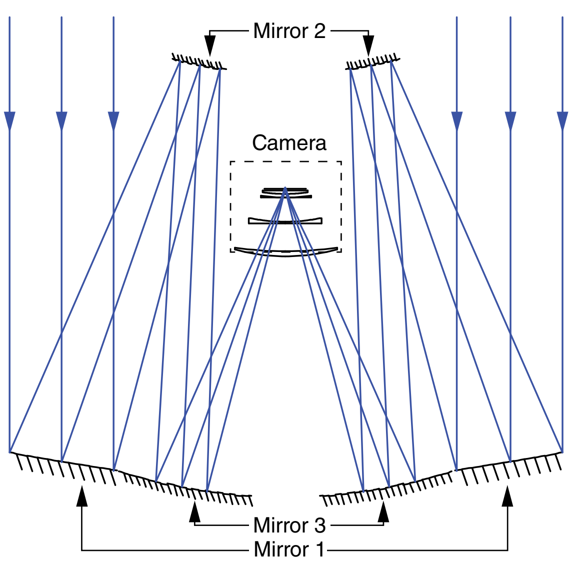
Office of Science. "Furthermore, all mass in the universe—dark matter and normal matter—accounts for only about a third of the total energy density. The other two-thirds is dubbed dark energy." Do dark matter and dark energy exist only in deep space? Or do they also exist in our solar system and even around Earth, as well? Do they help comprise our planet and our physical bodies? Such are the questions that researchers will seek to answer with LSST.

In addition, light from bright galaxies can be distorted by the gravitational force from dark matter caught in the line of sight. This gravitational lensing can be understood by measuring the shapes of galaxies. Schneider says, "LSST may be the final ground-based survey instrument built in our lifetimes to measure that effect with subpercent precision, map the mass in the universe, and thereby locate dark matter and dark energy and help figure out what they are."

Space Invaders and Cosmic Origins

Although mystery currently shrouds the composition of dark matter and dark energy, scientists understand all too well the compositions of hidden "space invaders"—objects on an intercept course with Earth. The wide, fast, and deep features of LSST make it unquestionably the most efficient way of identifying near-Earth objects (NEOs) whose orbits cross Earth's and so could one day strike our planet. The search for NEOs is the primary reason for the hourly revisits programmed into LSST's survey cadence. The time between the first and second pairs of images is enough to show differences revealing an NEO, which can then be tracked and its orbit determined. If LSST's 10-year mission is extended by a couple of years, the telescope could detect 90 percent of all potentially hazardous NEOs larger than 140 meters in diameter. LSST could also provide 1 to 3 months of warning for those as small as 45 meters. Even an NEO with a diameter of less than 100 meters could impact Earth with the force of a nuclear bomb. Advance notice offers the time needed to defeat these otherworldly threats. (See *S&TR*, December 2016, pp. 16–19.)

An important parameter of a telescope is its étendue, or "grasp," defined as the field of view multiplied by the surface area of the primary mirror. At 319 meters squared–degrees squared, LSST's étendue exceeds that of any current facility by more than a factor of 10. Such an enormous increase will lead to science opportunities never before possible.



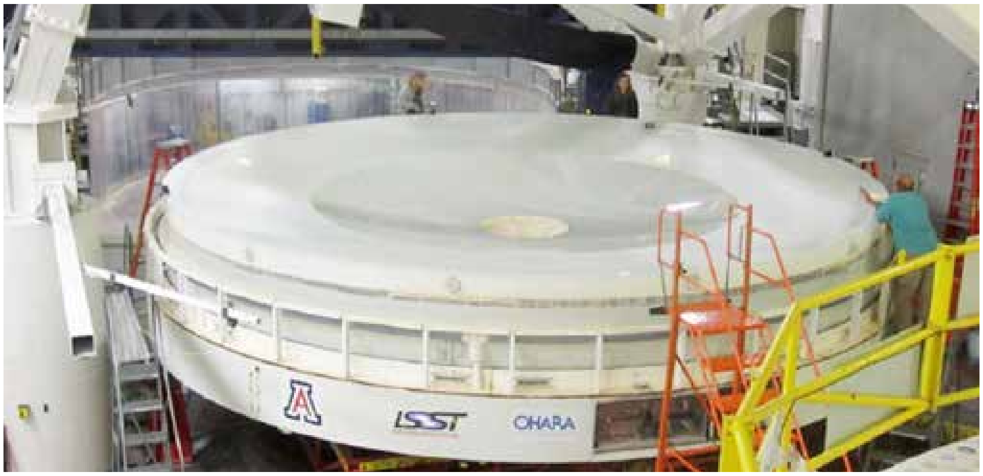
As shown in this ray diagram, light entering the telescope reflects between three mirrors and then is focused through three lenses and a filter before striking the camera's detector. (Image courtesy of Lynn Seppala.)

Images taken with such great breadth, speed, and depth will capture fleeting astronomical events, possibly recording up to 4 million supernovas, for instance. By better recording objects in the solar system and the rest of the Milky Way and how they move, scientists will more clearly understand how Earth's solar system and galaxy formed. Putting these varied puzzle pieces in place could unravel the mysteries surrounding the universe, including Earth's cosmic origins.

Beyond Galileo

LSST must move like a racecar among telescopes to accomplish such science goals—a great challenge considering that the camera by itself weighs 3,060 kilograms. The entire moveable structure of the telescope, including the camera, tips the scales at 272,000 kilograms. To achieve its speedy performance, LSST's design needed to be as compact as possible. This contradicts the conventional wisdom that to see wider and deeper into space, a telescope and its optics must be built as big as possible. Materials and fabrication limitations alone would prohibit the type of telescope—a long tube capped by a lens at each end—that has been widely used ever since Galileo used one to first identify Jupiter's moons. Moreover, the machinery to wield such a telescope would be colossal. Moving such a behemoth between locations and waiting for the vibrations to subside would be measured in hours instead of seconds, rendering the telescope useless for any science dependent on rapid scanning. In short, a breakthrough in telescope design was needed.

The breakthrough began in 1998, a year after the first paper positing the existence of dark energy was published, when Roger Angel of the University of Arizona proposed a three-mirror design with a primary-mirror diameter of roughly 6 meters. As the potential for additional capabilities became more apparent, this diameter was increased to 8.4 meters. Kahn notes, "A lot of refinements radically changed the early design concept, and



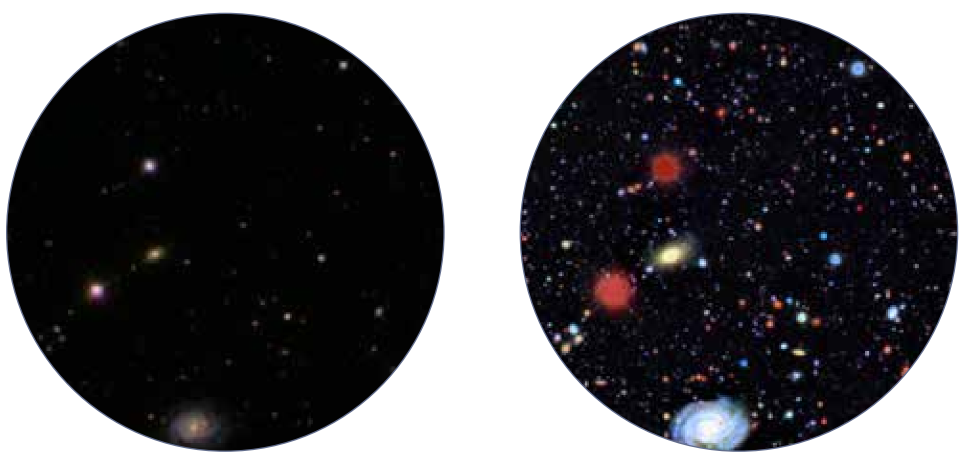
The photograph shows one of LSST's many design innovations—an integrated mirror monolith with a dual optical surface combining the primary and tertiary mirrors. (Photograph courtesy of LSST Corporation.)

Livermore physicist Lynn Seppala played a very important role. A lot of his ingenuity went into it." Seppala, now retired, was tasked with evaluating Angel's optical design to determine whether the sizes, shapes, and placements of the optical elements—lenses, mirrors, and filters—would meet the demands of LSST. He determined the design would theoretically work but would be essentially unbuildable because of its complexity, size, and lack of robustness. More iterations followed. "I wanted to make everything as foolproof as possible," says Seppala. He felt ease of manufacture was essential to LSST's optical design. "How are you going to test it? And how are you going to certify it? My strategy was to carry out, with each design iteration, a set of simple fabrication tests for all of the lenses, the three-mirror telescope without the camera, and the assembled three-lens camera corrector. Simplifying these tests would increase reliability both during fabrication and in assembling the camera and telescope."

A groundbreaking approach that further simplified the optics and drastically reduced the length of the telescope came when Seppala helped optimize a design where the primary mirror (M1) and the tertiary mirror (M3) were combined into the same piece of glass, eliminating a set of support and alignment structures. The weight-savings appeal of this dual optical surface eventually inspired new designs, which have been patented by the Laboratory. Miniature versions of this technology can be found in tiny CubeSat satellites. (See *S&TR*, April/May 2012, pp. 4–10.) Seppala also emphasized keeping the 3.4-meter-diameter secondary mirror (M2) as spherical as possible for ease of manufacture without sacrificing performance. The enormous size of this mirror can be understood by noting that the secondary mirror of any existing telescope could fit easily inside the center hole of M2. LSST's giant camera also conveniently fits inside the center hole, greatly simplifying its mounting.

Because the camera is so sensitive, its detector is sealed inside a vacuum chamber, and three lenses correct the path of inbound light from the mirrors before striking the detector. At a diameter of 1.55 meters, the first lens through which the light passes is also the largest high-performance optical glass lens ever built. The third lens (L3) also acts as the vacuum chamber window. Between the second lens and L3 will fit one of six filters, which can be switched in and out by the armature of a fast-acting carousel, similar to the mechanism that changes records in an old-fashioned jukebox. Each filter has an individualized coating that allows through only light in a specific wavelength range. By uniformly scanning the sky with each filter, LSST will permit multicolor analyses.

Whereas the mirror coatings must reflect as much light as possible and the filter coatings must exclude all but specific bands of light, LSST's lenses have antireflection coatings to maximize the amount of light passing through them. Fused silica, an amorphous form of quartz, is the glass used to make M2 and all the lenses and filters. A special spin-casting process was used to create a single piece of honeycomb-backed



The dramatic improvement in stargazing capabilities that LSST will enable is seen in this side-by-side comparison of the same sector of space revealed by (left) the recent Sloan Digital Sky Survey and (right) in a simulated LSST photograph. (Images courtesy of LSST Corporation.)

borosilicate glass, which was then polished into the shapes of M1 and M3. This approach reduced overall weight by 90 percent over conventional methods, making the telescope lighter and speedier to maneuver. This lightweight, compact design allows the mirrors and camera to be more easily and safely removed, minimizing down time for maintenance.

Wide and Deep

A telescope's field of view determines how much of the sky it can see. The entire sky from horizon to horizon encompasses a 180-degree field of view. A full Moon is only 0.5 degrees wide, but ground- and space-based telescopes typically have a field of view that is only a fraction of this lunar width. LSST, in contrast, boasts a gigantic 3.5-degree field of view, capturing an image area equivalent to 49 Moons. Needing fewer images to capture the entire sky speeds up the survey. LSST will also collect more light in less time than other telescopes, enabling viewing of objects as faint as 24 on the astronomical magnitude scale—roughly 10 million times dimmer than what is detectable by the unaided human eye. By combining images, LSST can reach even deeper, to a magnitude of 27. By comparison, relatively bright Saturn registers 1 on this scale, the stars of the Big Dipper 2, and the moons of Jupiter 5. The limit for the Hubble Space Telescope is a magnitude of 31, partly because of its orbit in space. Although able to detect dimmer objects than LSST can, Hubble has a very narrow field of view, equivalent to only a fraction of a full Moon.

Although Hubble does not have to contend with Earth's atmosphere, LSST faces atmospheric disturbances that threaten to drastically reduce image quality, as well as changes in environmental conditions and the shifting pull of gravity as the massive mirrors change positions. One way Livermore strove to minimize such effects was by drawing on its experience in adaptive optics (AO), a technique the Laboratory helped pioneer. (See *S&TR*, September 2014, pp. 4–12.) Another optics innovation incorporated into LSST is an active optics system that Livermore researchers developed in collaboration with the National Optical Astronomy Observatory. In this system, the reflective surface of all three mirrors is finely tuned by networks of actuators mounted on the backs of the mirrors. By slightly changing a mirror's shape, the actuators compensate for distortions in light caused by the small deflections of mirror surfaces that arise from changes in temperature or gravitational pull. In short, AO and active optics are key to LSST achieving its goals.

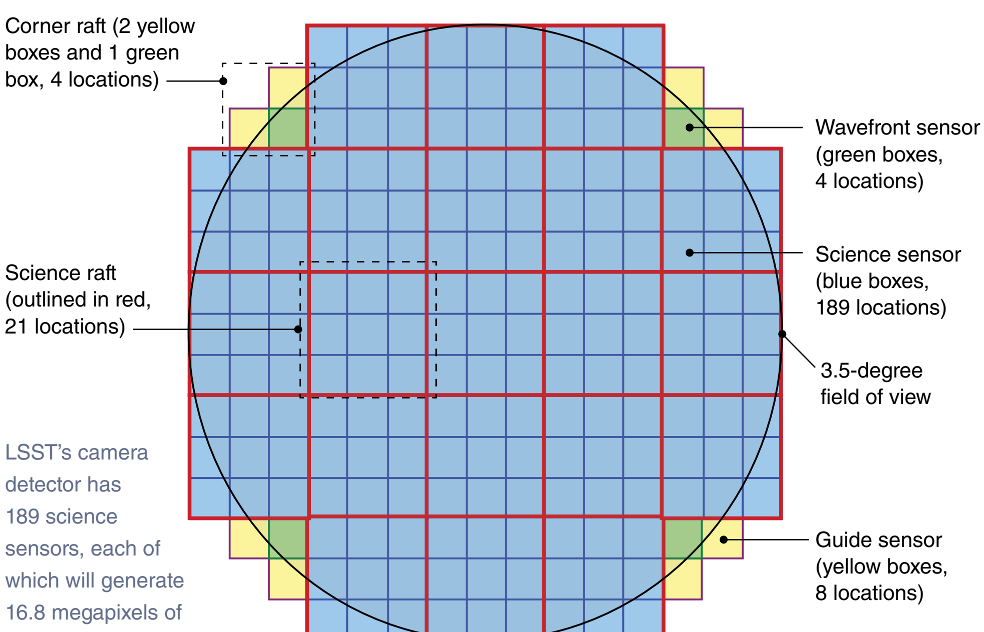
On the Shoulders of Giant Optics

The Laboratory is lending its optics expertise in other areas, as well. Livermore engineer Scott Winters, the optics subsystems manager for the LSST camera, states, "Livermore has a history of building complex optical systems, the latest being the National Ignition Facility (NIF). From fabrication, coatings, assemblies, and precision cleaning to other aspects, we're able to harvest this knowledge and apply it directly to the camera's optical systems. In short, LSST is getting years and years of experience and lessons learned from the Laboratory."

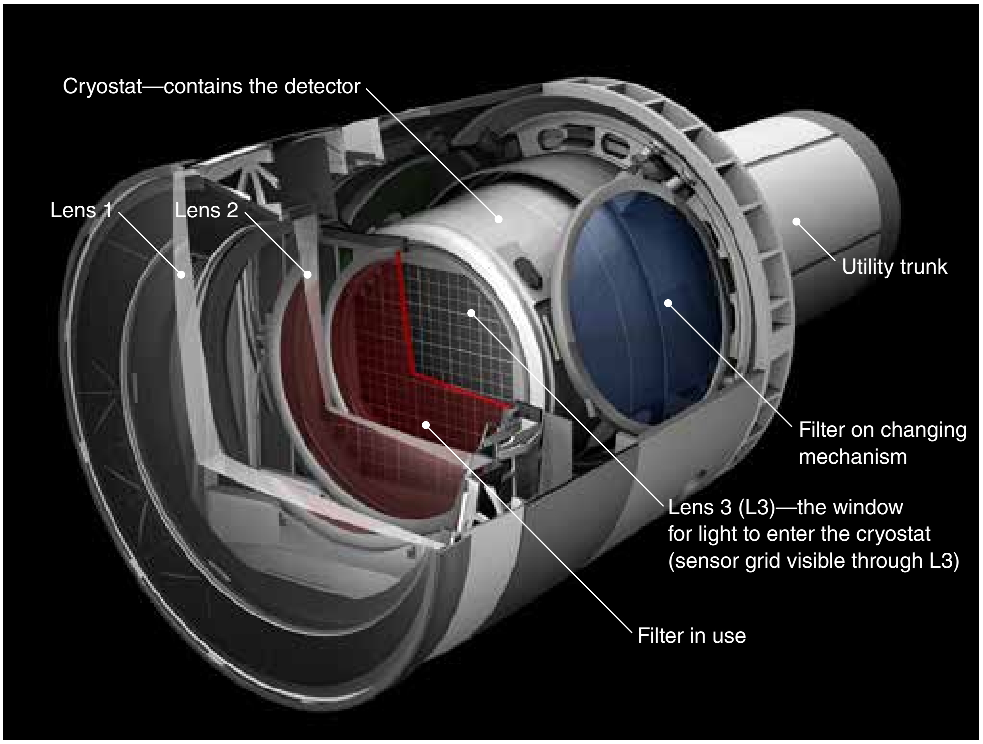
Livermore personnel led the procurement and delivery of the camera's optical assemblies, which include the three lenses, and six filters, all in their final mechanical mount. Livermore focused on the design and then delegated fabrication to industry vendors, although the filters will be placed into the carousel interface mount at the Laboratory before being shipped off to SLAC for final integration into the camera. Partnering with industry has been the approach taken to build NIF and the Laboratory's other large laser systems. Winters states, "LSST is all about leading-edge technology, including the world's largest camera, so it's an exciting project. We're able to do amazing things by engaging various people in cutting-edge work. This is a great win–win for everyone."

Super-Sensitive Sensors

SLAC is managing subcomponent integration and final assembly of the $168 million camera, which is currently over 60 percent complete and due to be finished by 2020. Livermore engineer Vincent Riot, interim project manager of the camera, says, "Many challenges come with making the largest camera in the



LSST's camera detector has 189 science sensors, each of which will generate 16.8 megapixels of image data.



With a maximum diameter of 1.65 meters, a length of 3.73 meters, and a mass of 3,060 kilograms, LSST's camera will be the largest ever made. (Image courtesy of LSST Corporation.)

world." The camera's detector is a bee's-eye mosaic of 189 ultrahigh-purity silicon sensors, each 100 micrometers thick. Each captured image is 4,096 by 4,096 pixels in size, or 16.8 megapixels in all. The entire detector thus delivers a combined pixel count of 3.2 gigapixels. In each corner of the detector are a wavefront sensor and two guide sensors, which ensure image quality by monitoring surrounding conditions and feeding back data that drive corrective measures, such as with the active optics system. Riot explains, "The wavefront and guide sensors must be sensitive to a very broad range of wavelengths, from deep ultraviolet to infrared, and must have very low noise and be very flat."

After light circuits its way through the optics, an image forms on the detector's 63.4-centimeter-diameter focal plane. The compactness of the telescope's optics makes the focus very unforgiving. A blurry image could result if any part of the detector surface is misaligned to the incoming light by more than 11 micrometers—approximately one-fifth the diameter of a human hair. The camera's sensors are charge-coupled devices, which create images by converting the incoming light (photons) into electrons. For this reason, the vacuum vessel that houses the camera is cryogenically cooled to an operating temperature of –100 to –80 degrees Celsius. This cooling has twin benefits—preventing overexposure defects, which tend to occur when such sensors are operated at warmer temperatures, and reducing signal noise from various sources. This improvement allows electrons to be more accurately counted and therefore produce the best images possible.

Petabyte Free-for-All

Each 3.2-gigapixel image will be saved as an image file roughly 6 gigabytes large. Because LSST needs only 2 seconds to read out raw data between exposures, the telescope will amass roughly 15,000 gigabytes of image data each night. Compounding this over 10 years of operation yields a total of 60 petabytes (10^{15} bytes). The images compiled in a single visit will be immediately compared, and if a difference is found, suggesting some event, an alert will be automatically issued within 60 seconds. Each night, LSST is expected to detect about 10 million such events. Single images and catalogs of images will be frequently streamed online, and the LSST computational system will do more advanced processing, such as time-lapse movies. Much of this imagery will be made available for free so that the public can learn about discoveries in near real-time and participate in "citizen science" opportunities.

Schneider explains, "The data science aspect of LSST is highly important. Rather than study one object at a time, which was the astronomy model of the past, LSST is actually statistical analysis conducted on a large, complicated dataset, and to do the really big science requires thinking about algorithms and computing in a different way than astronomers are used to doing." LSST's immense repository of data will not only drive research in new ways but also necessitate all-new studies on how to better analyze tremendous amounts of data. Livermore's wide-ranging contributions have elevated LSST to the forefront of science and technology. Soon LSST will deliver the promises of world-changing astronomy and a clearer understanding of how we fit into this wide, deep, fast universe of ours. Who knows where this journey will take us?

—Dan Linehan

Key Words: active optics, adaptive optics (AO), dark energy, dark matter, data science, dual optical surface, étendue, field of view, gigapixel camera, Large Synoptic Survey Telescope (LSST), National Ignition Facility (NIF), near-Earth object (NEO), optical design, spin-cast mirror, telescope, ultrahigh-purity silicon sensor.

For further information contact Michael Schneider (925) 422-4287 (schneider42@llnl.gov).